Breakage and shear behaviour of rock joints with intermittent material bridges

Abstract
Shear failure of a rock mass usually occurs along existing joints. But additional breakage of material bridges, which are located between joints of generally limited extension, is frequently involved. This complex fracture and failure process has been investigated in a series of direct shear tests with a new shear device specifically designed for this purpose. The tests have been performed on specimen slabs, cast of model material respectively prepared from hard rock, and incorporating a number of parallel cracks in an en-echelon arrangement along the central shear axis. These cracks are supposed to simulate a discontinuous rock joint interrupted by material bridges.

The beginning of shearing in such a joint constellation is characterized by the formation of new fractures which eventually bisect the material bridges and lead to a complete discontinuity. Thereafter, further shear displacements take place. The final form of such an initially intermittent discontinuity, reached after large shear displacements, is that of an intensively broken and mylonized shear zone.

The shear resistance of such discontinuous joints proved to be extremely variable during the entire shear process. According to the different mechanisms characterizing this shear process, the shear behaviour can be subdivided into three distinct phases of shearing, each of them characterized by at least one shear resistance maximum. The first phase of shearing is that of the actual rupture, initiated by the formation of wing cracks, starting from the existing cracks and growing into the material bridges, and concluded by the generation of additional new fractures connecting the primary cracks in the zone between the wing cracks. The complete separation of the material bridges in then obtained. The second phase of shearing is characterized by friction processes and volume increase in the shear zone. Finally, the third phase of shearing, reached after large shear displacements, is determined by sliding processes inside the strongly fractured shear zone.

In a large number of shear tests the geometrical parameters of the discontinuous joints as well as the loading conditions were found to influence the activated shear resistance in each phase of shearing to a noticeably different extent. The orientation of the initial cracks and the normal stress, however, were identified as the most influential parameters. Depending on the test conditions, an initially discontinuous rock joint can activate the largest shear resistance not just before rupture
but in one of the two subsequent phases of shearing as well. The shear strength of such a joint is therefore not necessarily overcome with the complete bisection of the rock bridges between the initial cracks, but might even be higher in a later stage of the shear process.

The type of failure occurring at rupture can clearly be identified as a tensile one. This follows from the direct shear tests as well as from numerical studies. There was no indication of shear cracks. The frequently decisive shear resistance in the second phase of shearing is not, as often assumed, characterized by sliding up the asperities of the joint. On the contrary, it could be demonstrated that a rolling friction mechanism acts during this phase. The rock bridges are cut out by the wing cracks and then actuated into rotation by subsequent shear displacements. Because of the shear strength reduction caused by this effect of rolling friction, the conventional shear models, based on simple sliding, frequently overestimate the shear strength of failure surfaces in rock masses. Up to now the exact magnitude of this shear resistance cannot be modelled in a reliable way since it is determined by the shape of the rock fragments, which act as rollers, and by the combined effects of rolling, sliding and fracturing mechanisms.

Finally, it has been demonstrated that the shear failure of rock structures develops in a more complex fashion than considered in conventional approaches. Often, however, the various shear mechanisms may result in a renewed stabilization of an incipient failure process. These model concepts, which cover the entire shear process, as presented in this thesis, should next be implemented into numerical models, leading to more realistic design procedures in the future.